Cosmology with the SKA Observatory

6ième colloque national Dark Energy

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Swiss Federal Institute of Technology Zurich

Marseille, 18 Nov 2022

The SKAO

credit: skatelescope.org

The SKAO

credit: skatelescope.org

The SKAO sky

credit: skatelescope.org

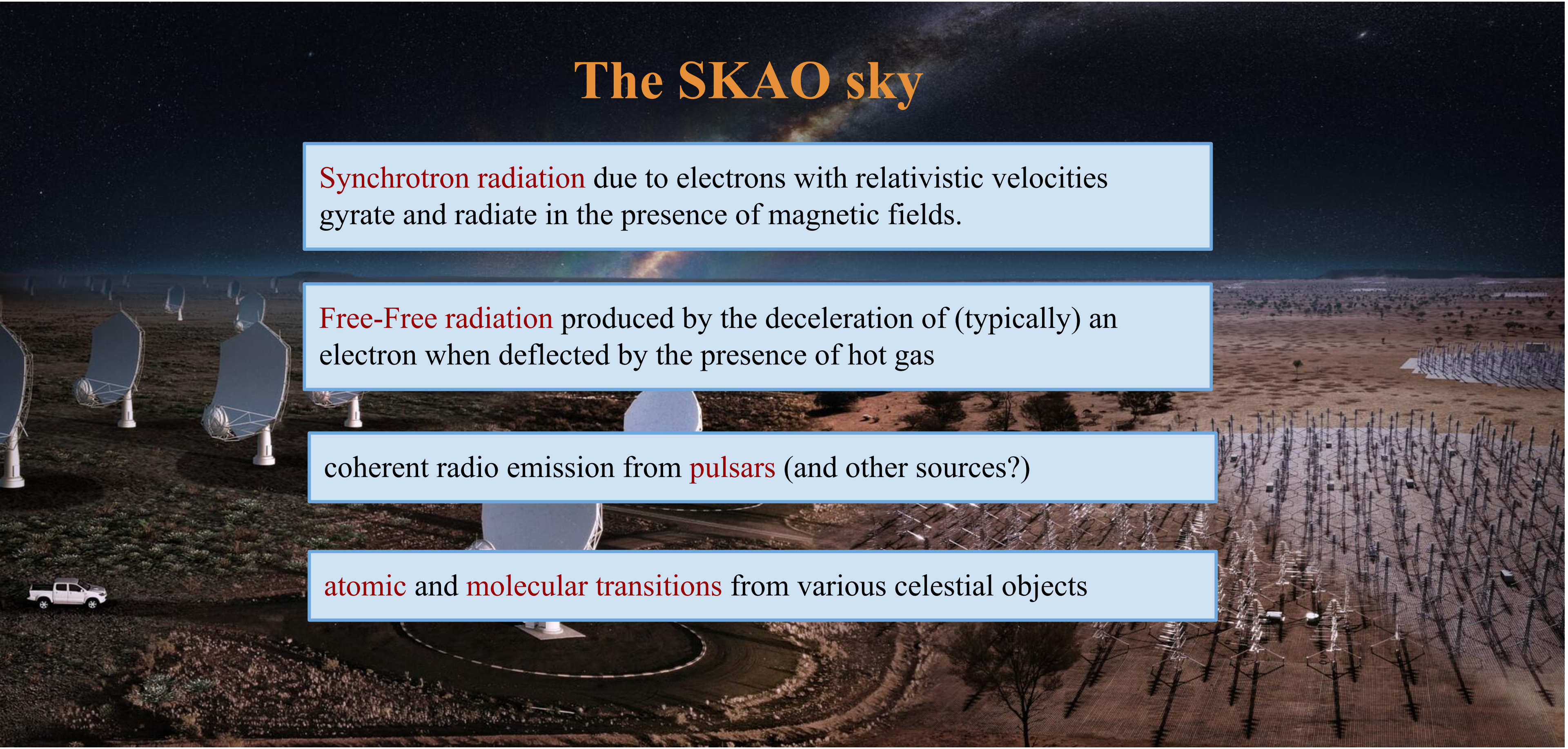
The SKAO sky

Synchrotron radiation due to electrons with relativistic velocities gyrate and radiate in the presence of magnetic fields.

Free-Free radiation produced by the deceleration of (typically) an electron when deflected by the presence of hot gas

coherent radio emission from pulsars (and other sources?)

atomic and molecular transitions from various celestial objects



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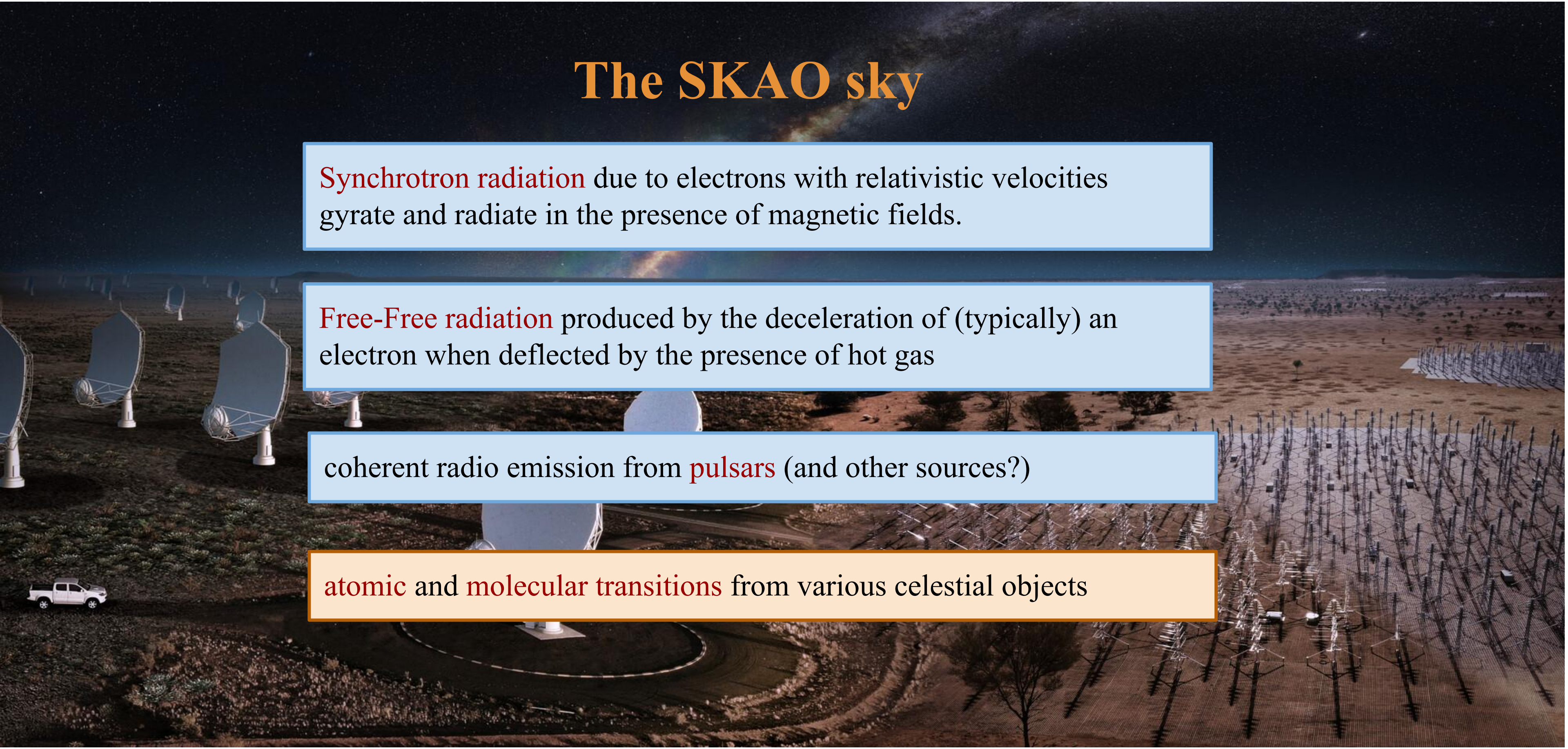

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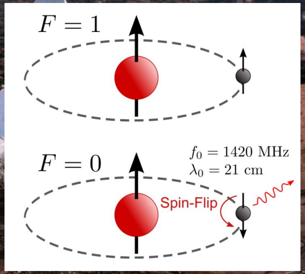
The SKAO sky

21cm (1420 MHz) line
of Neutral Hydrogen (HI)



post-reionization → Epoch of Reionization → Cosmic Dawn

credit: skatelescope.org

Cosmology Science Working Group

HI galaxies

Intensity Mapping

Continuum

Weak lensing

SKA Red Book (2020)

Cosmology Science Working Group

Simulations Coordination

Synergies

HI galaxies

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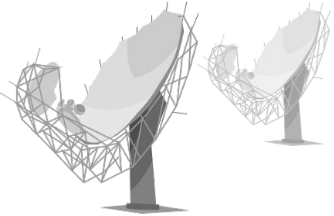

Precursor data
MeerKAT,
SuperCLASS (VLA)
ASKAP

Cosmology SWG annual meeting
Manchester,
17-19 Jan 2023

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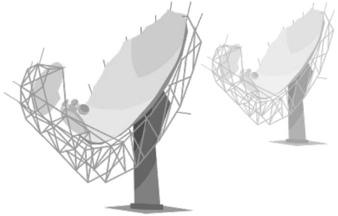

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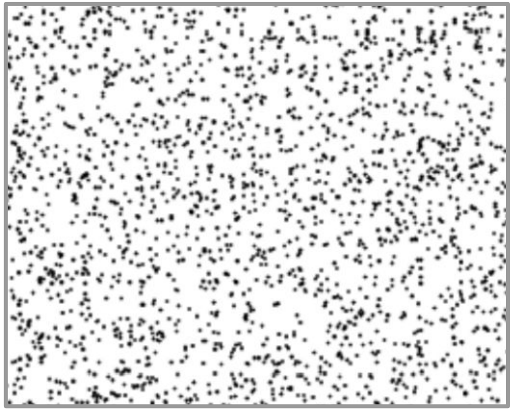
Intensity Mapping

credit: A. Pourtsidou

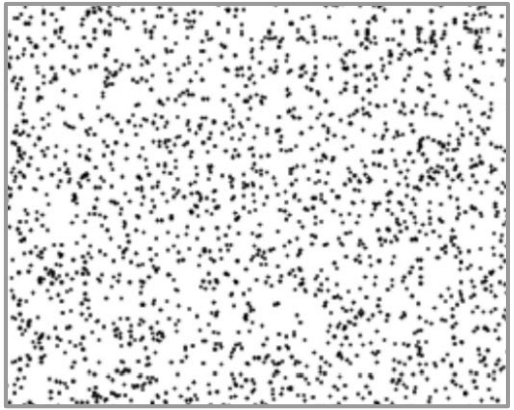


The distribution of **neutral Hydrogen**
is a biased tracer of the **matter clustering**
similar to galaxy surveys

In cosmology, **large scales** are fundamental

Intensity Mapping

credit: A. Pourtsidou



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In cosmology, **large scales** are fundamental

How can we efficiently observe cosmological volumes?

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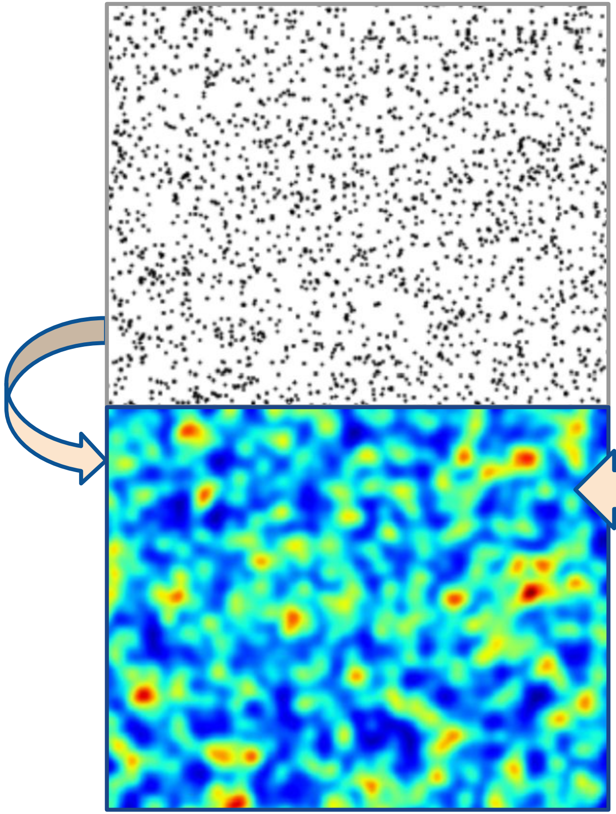

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Intensity Mapping: total intensity of the 21cm emission line in a **large pixel** (low spatial resolution)

Intensity Mapping

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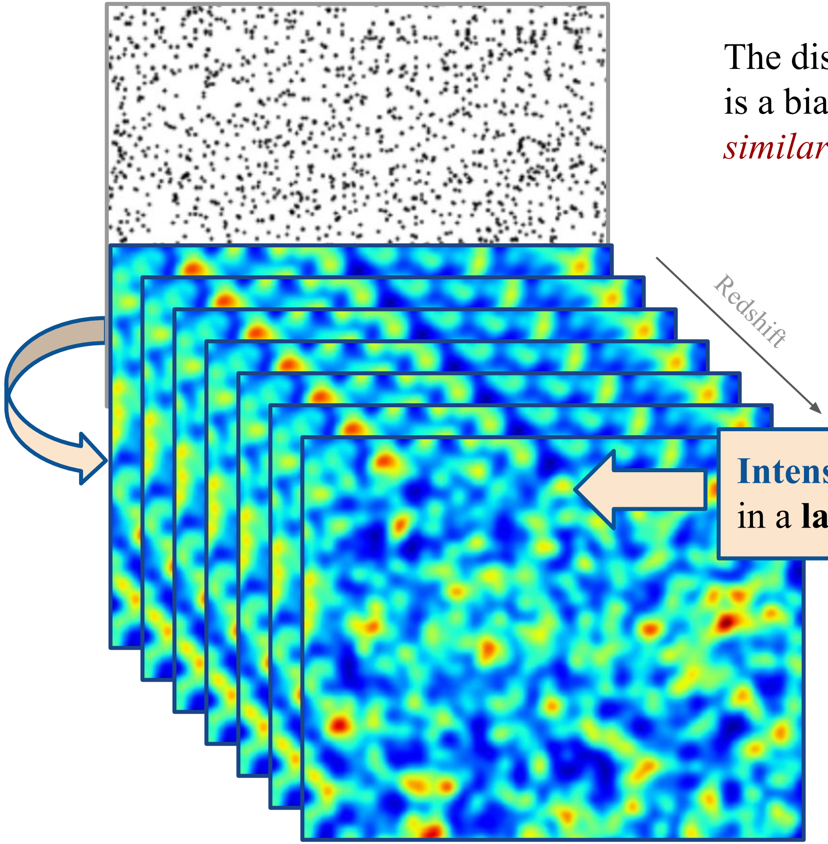

The distribution of **neutral Hydrogen**
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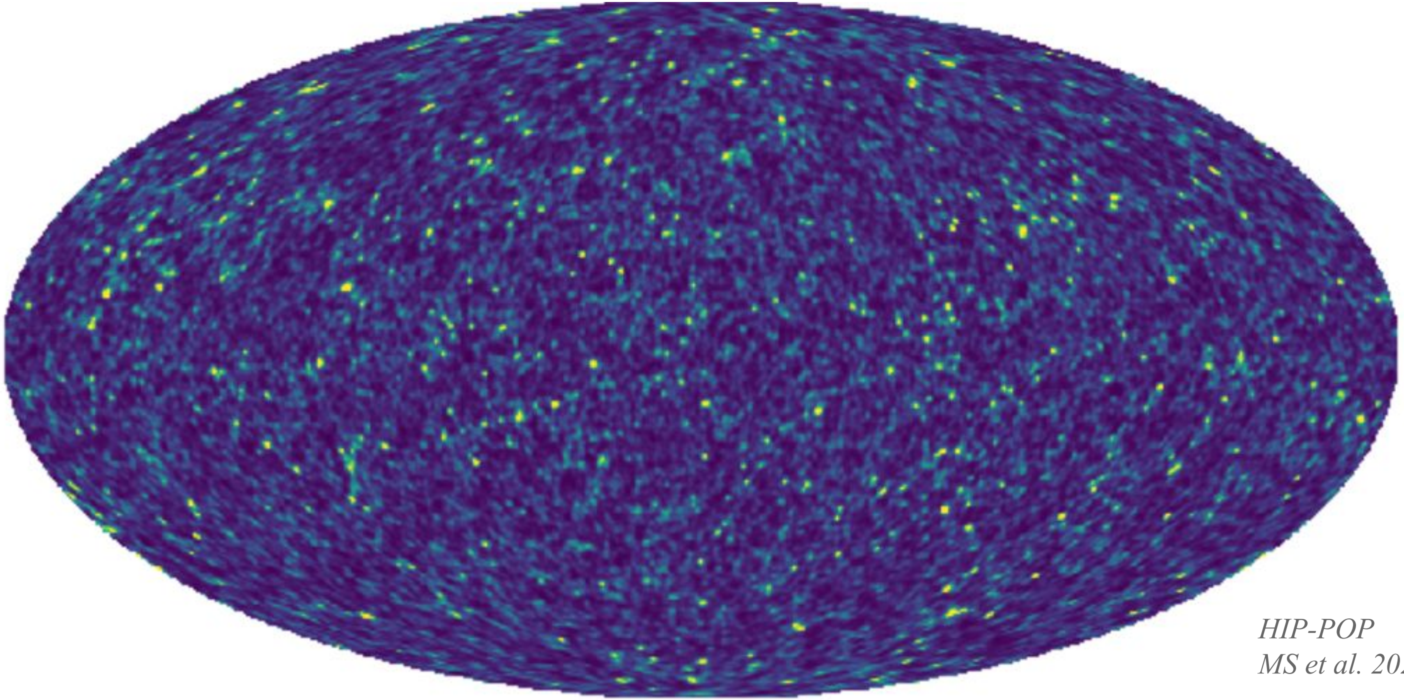
similar to galaxy surveys

Intensity Mapping: total intensity of the 21cm emission line in a **large pixel** (low spatial resolution)

different frequencies,
different z
high spectral resolution (tomography)

Key cosmological probe

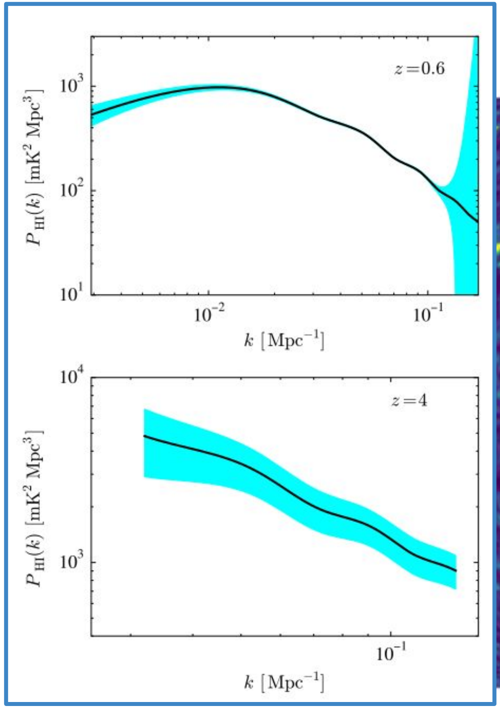
Key cosmological probe

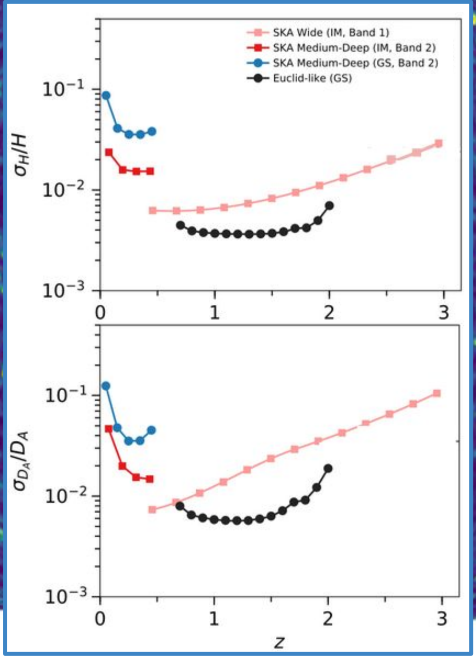


HIP-POP
MS et al. 2022

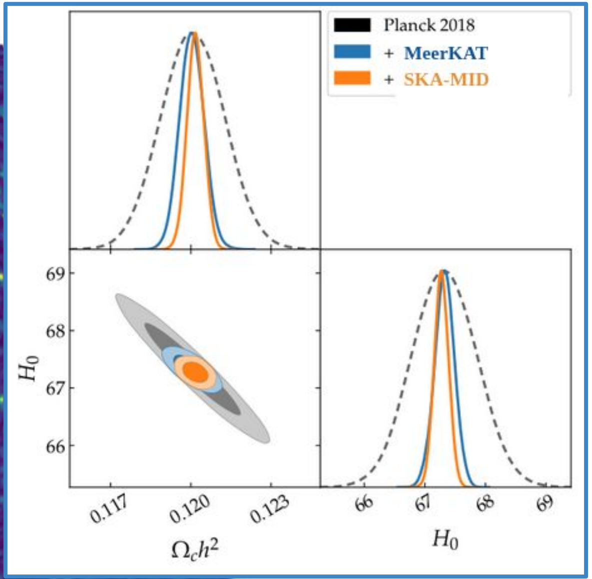
Key cosmological probe

SKA Red Book (2020)



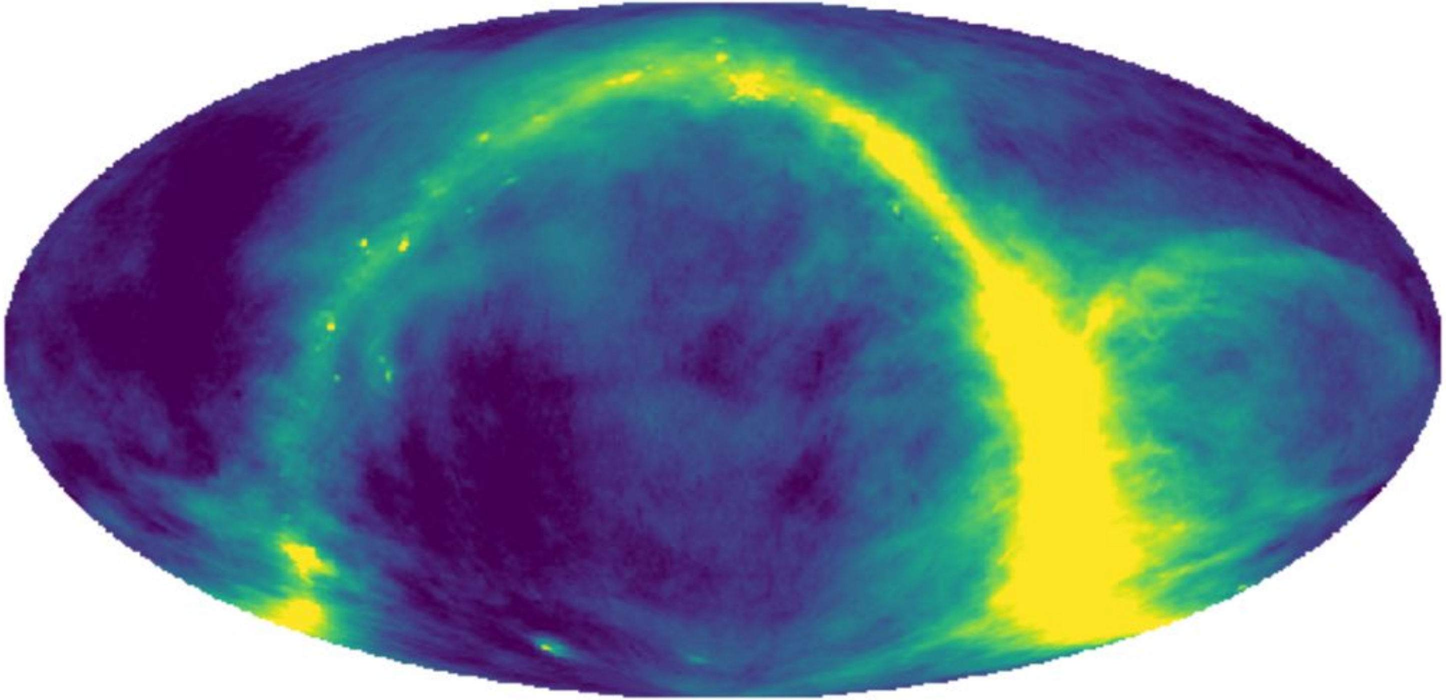


SKA Red Book (2020)



Berti, MS et al. 2022

The challenge of foregrounds



adapted from Haslam et al. (1982)

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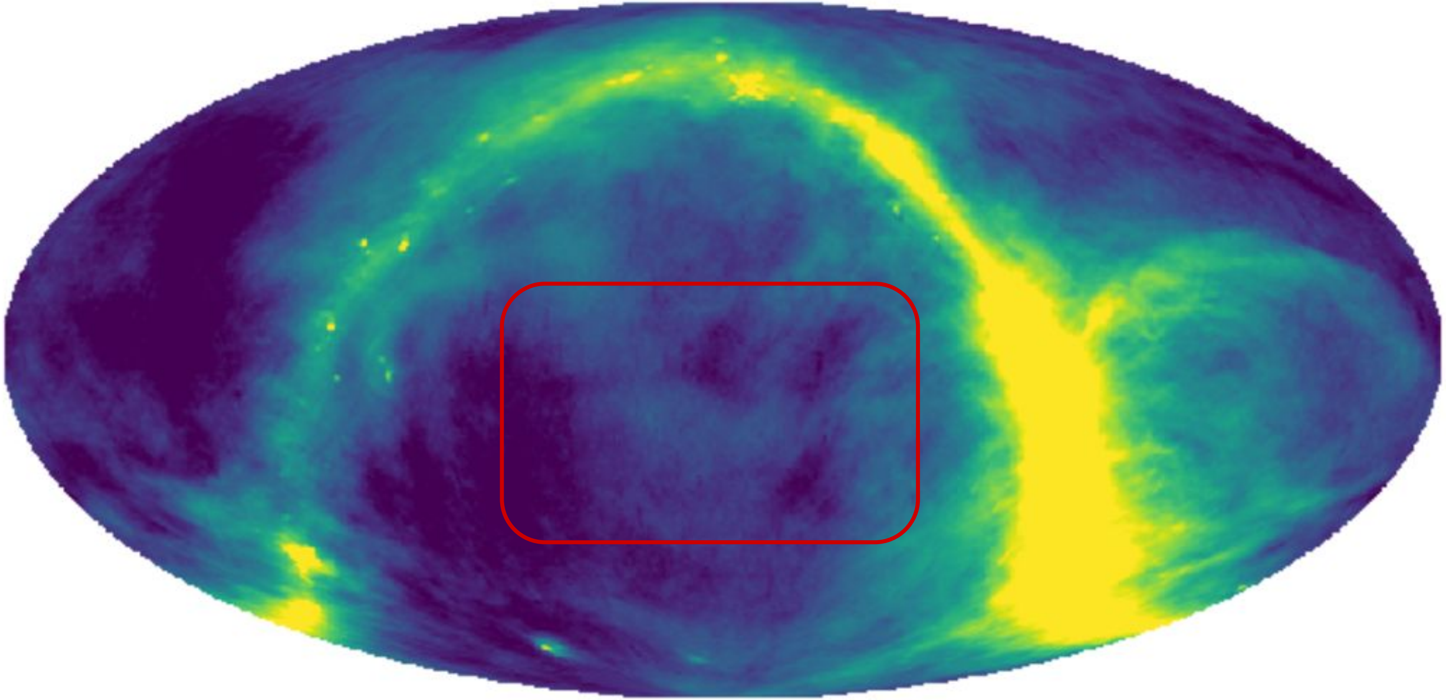

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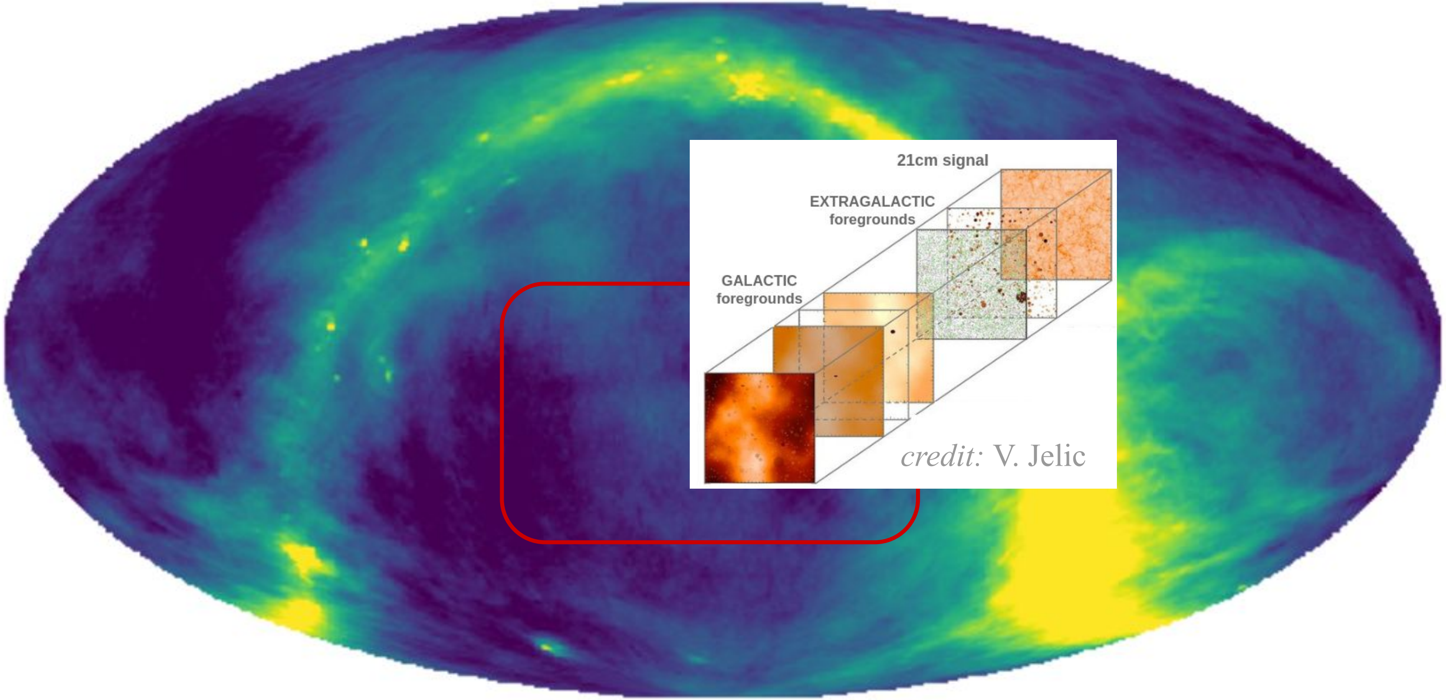

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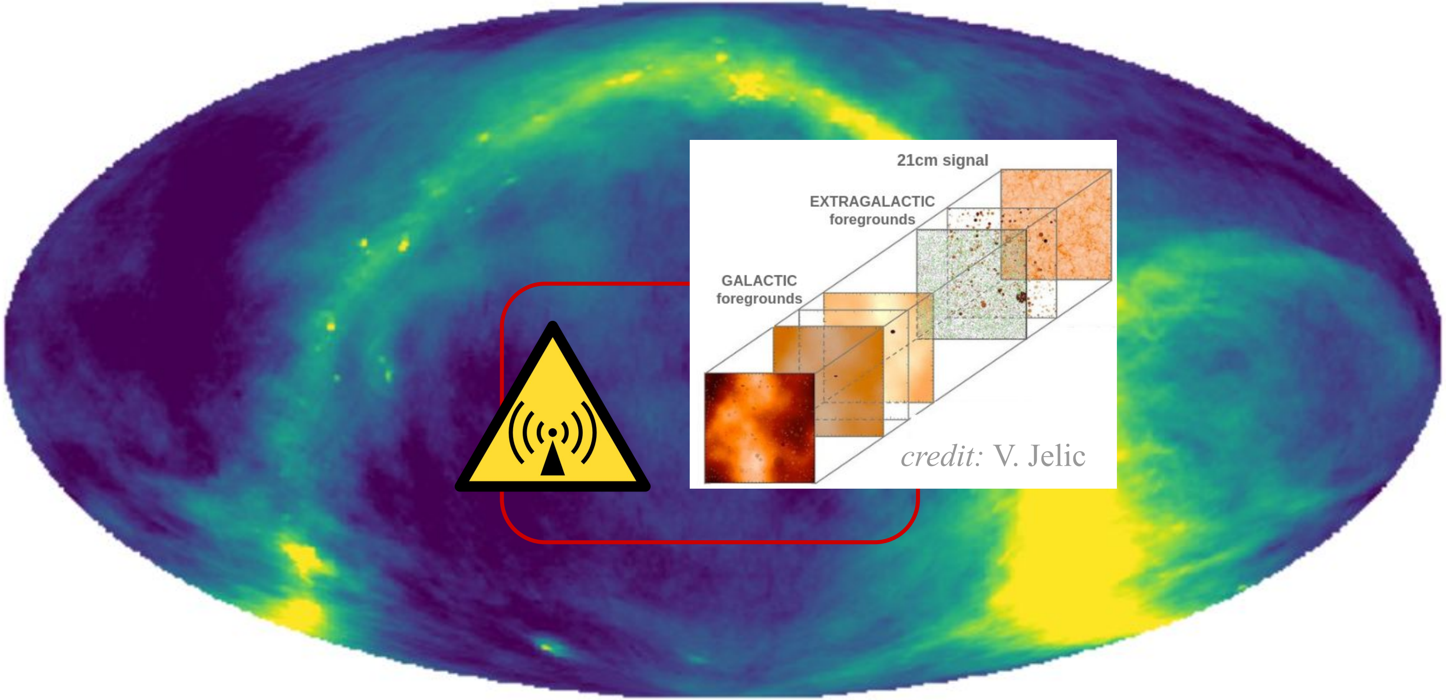

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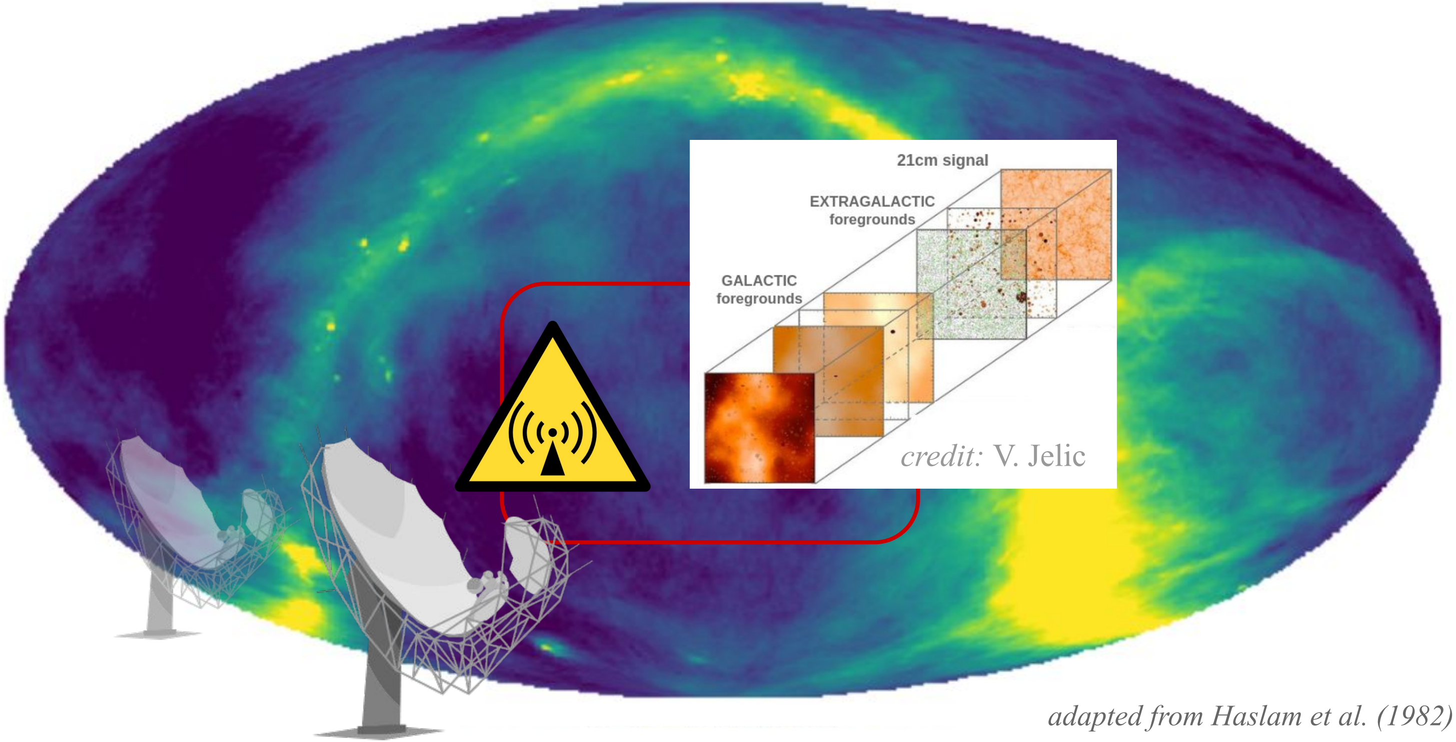

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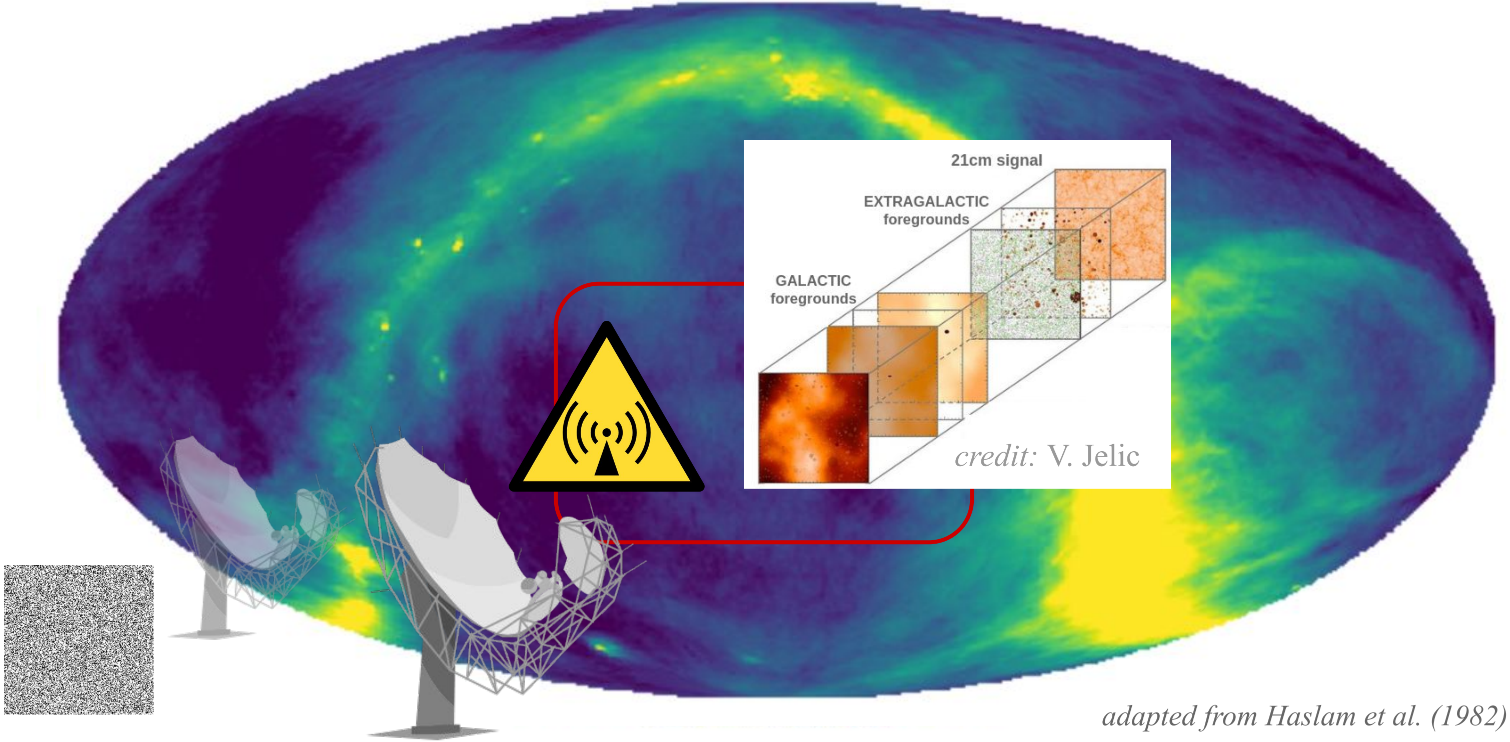
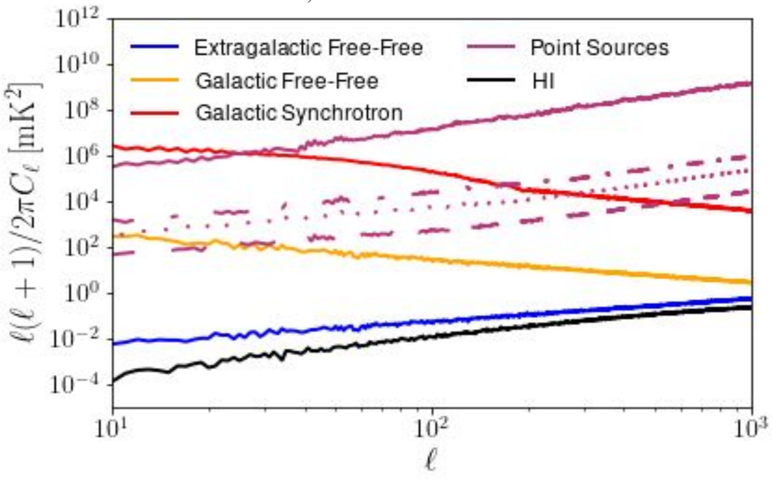
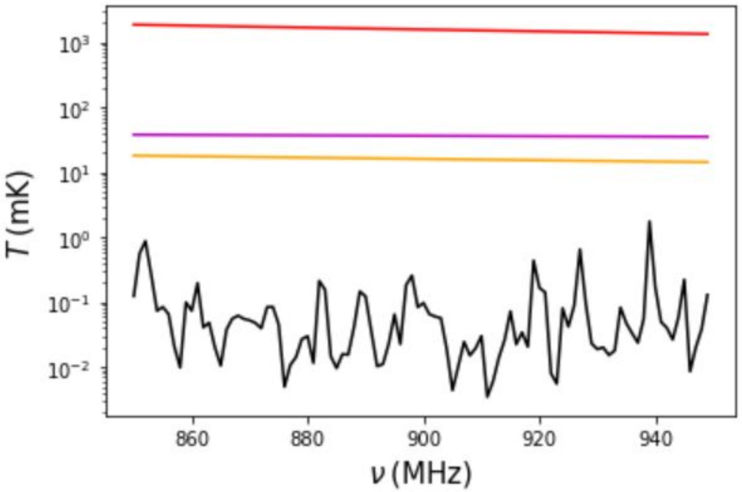


adapted from Haslam et al. (1982)

Properties of the foregrounds

Matshawule, MS et al. 2021





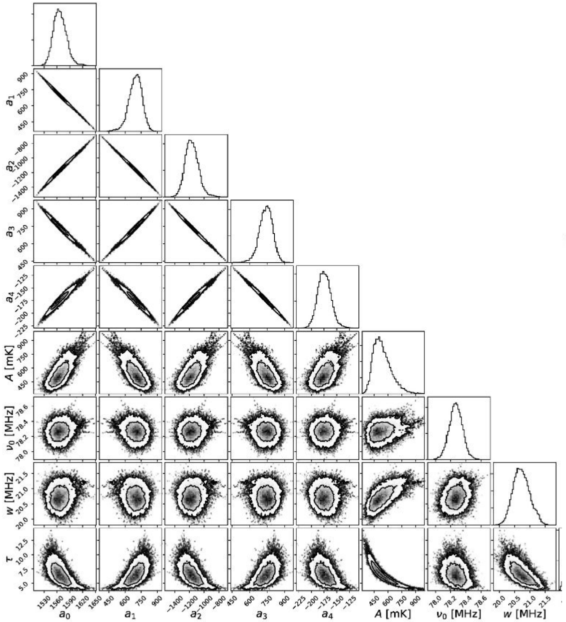
- ❑ foregrounds are orders of magnitude stronger than the 21cm signal
- ❑ their frequency behaviour is smooth (highly correlated)

Questions:

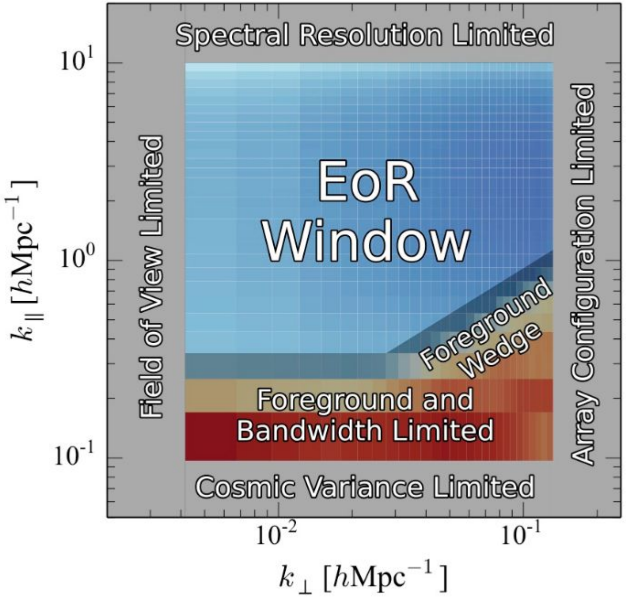
- ❑ Can the properties of the foregrounds be used to separate them from the pristine **21cm signal**?
- ❑ **Even if we add some realism to our simulations?** (beam response,noise,RFI, polarization leakage, ...)

Dealing with foregrounds

Various strategies: e.g. **modelling**, **avoidance** and **separation/cleaning**



Bowman et al. (2018)



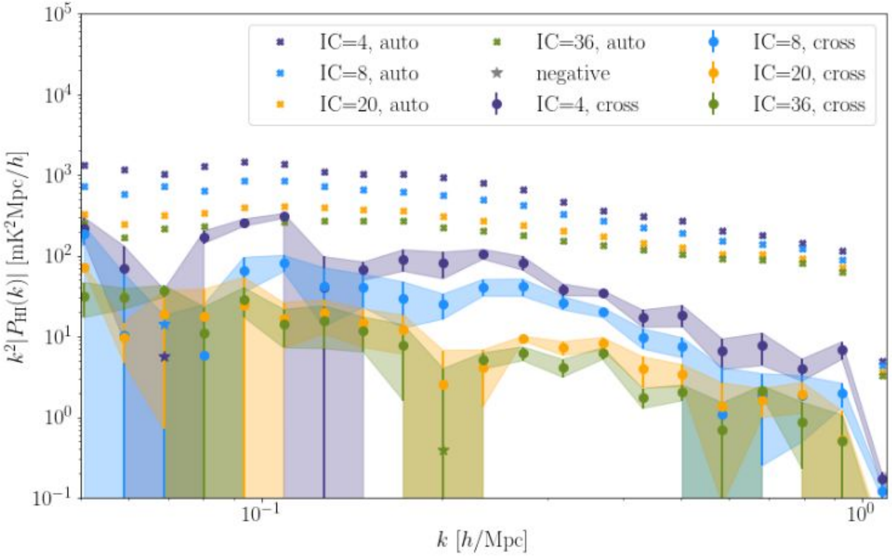
Liu et al. (2014)

separation/cleaning:

PCA, kPCA, FastICA, GMCA, GPR, ML-GPR

With GBT data

Wolz et al. 2022



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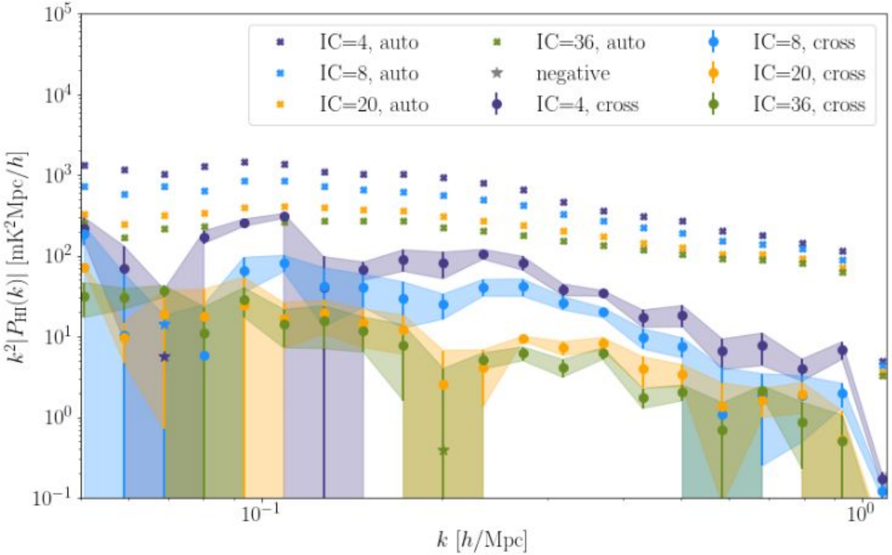
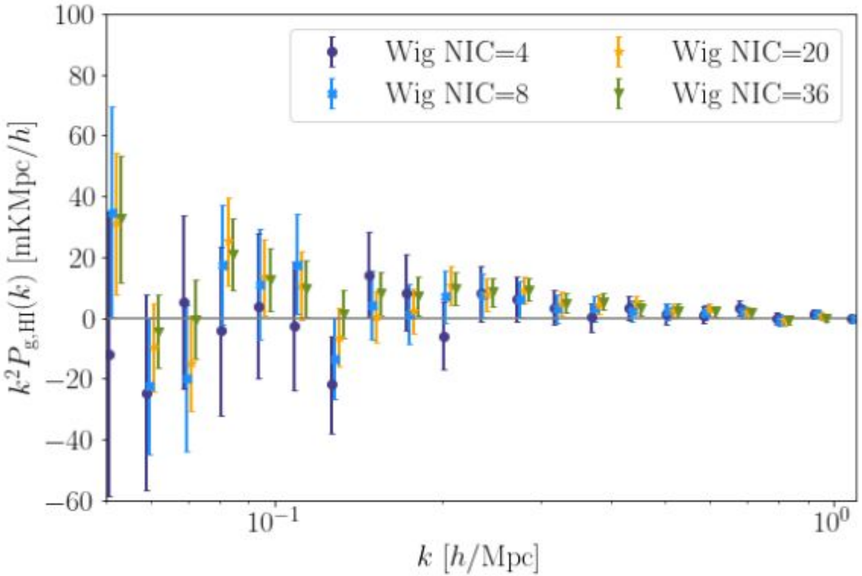
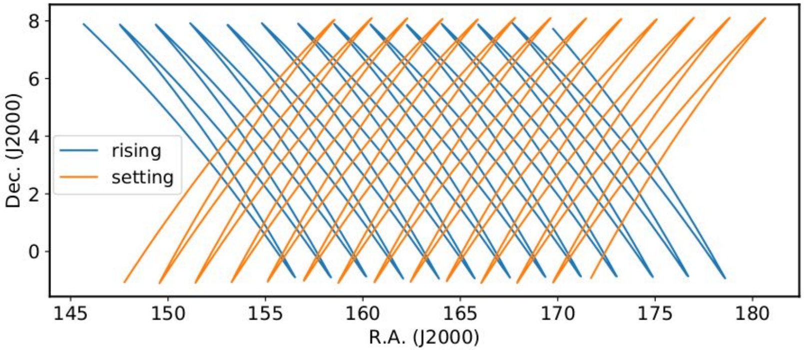
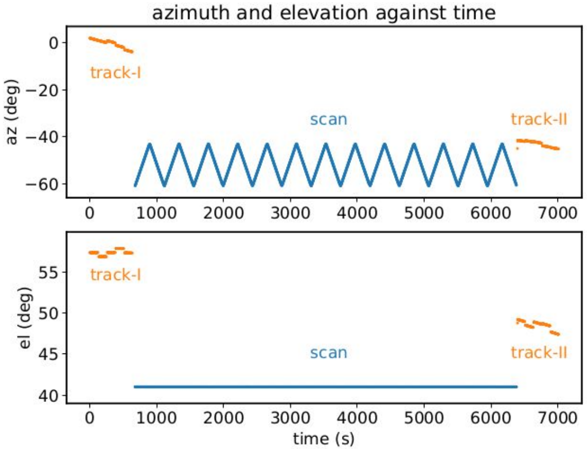




Intensity Mapping with MeerKAT

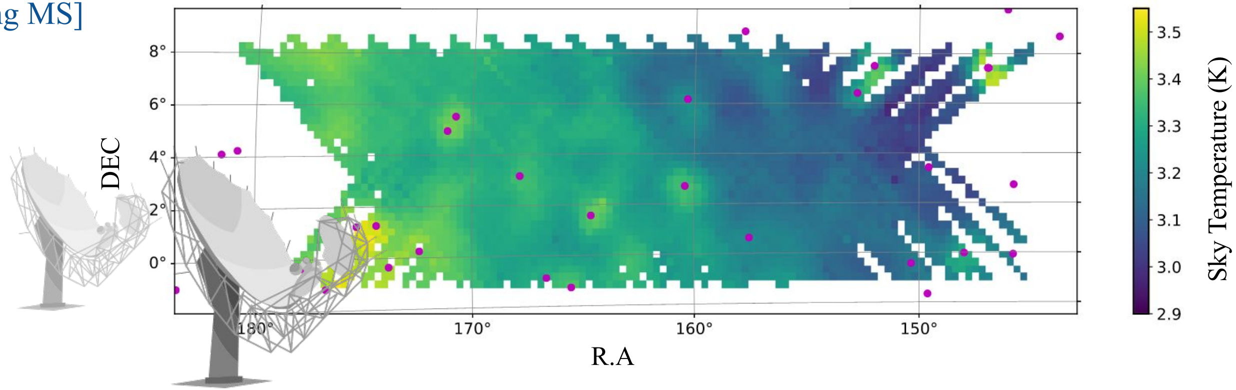
Antennas	All 64 MeerKAT dishes
Observation mode	Single-dish
Frequency range	0.856-1.712 GHz
Frequency resolution	0.2 MHz
Time resolution	2s
Exposure time	1.5hr x 7 scans
Target field	WiggleZ 11hr field ($10^\circ \times 30^\circ$)





MeerKAT observations

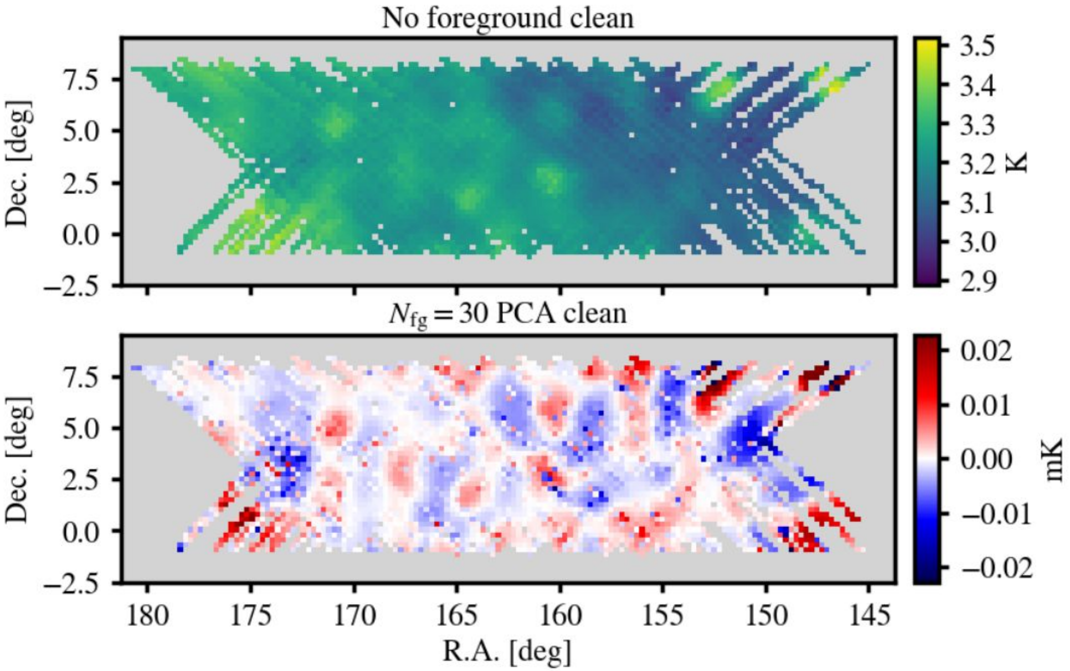
Wang et al. 2021
[including MS]



MeerKLASS: 64 MeerKAT antennas used in **single-dish mode**

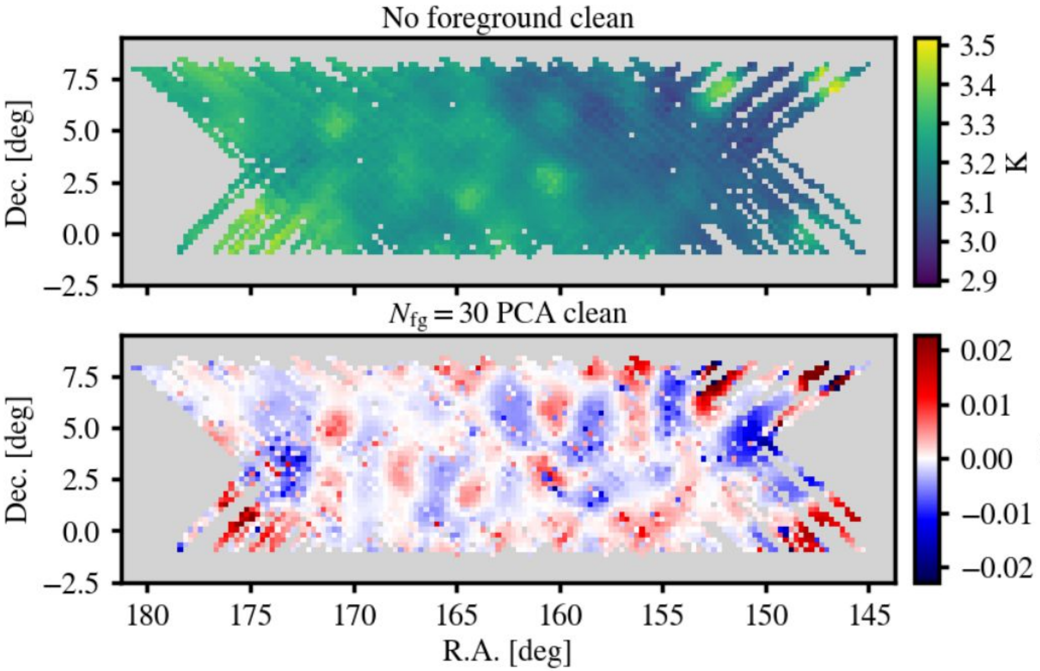
- ❑ first successful calibration of **intensity mapping data from MeerKAT**
- ❑ L-band: 850-1700 MHz (4096 channels)

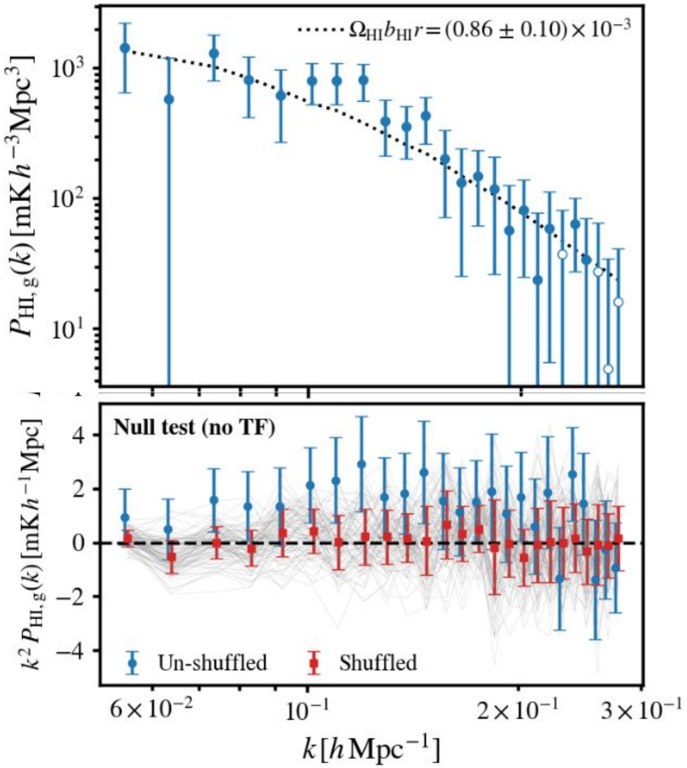
MeerKLASS results



Cunnington et al. 2022 [including MS]

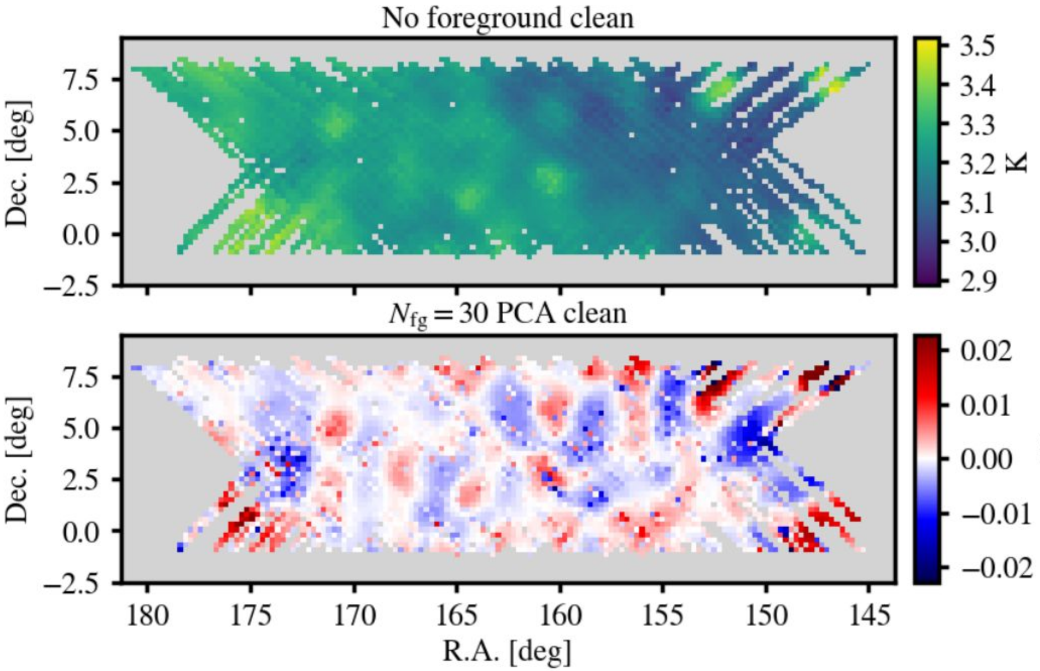
MeerKLASS results

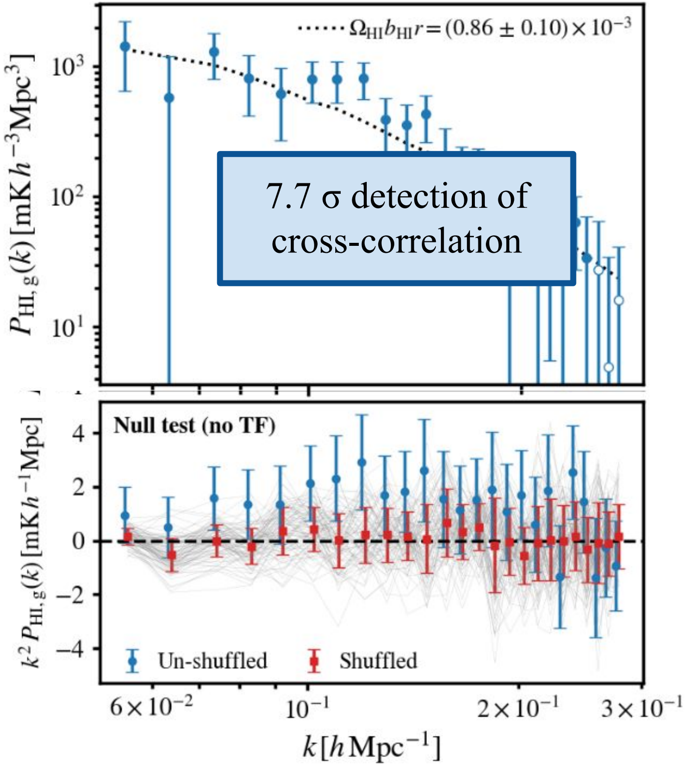




Cunnington et al. 2022 [including MS]

MeerKLASS results





7.7 σ detection of cross-correlation

Cunnington et al. 2022 [including MS]

In summary

We have:

21cm intensity mapping data difficult to clean (signal only in cross-correlation)

Simulations that are still not a realistic representation of the actual data

Cleaning methods that have still to be extensive tested with realistic simulations

We would like:

More and better data

More realistic simulations mimicking the data

More sophisticated cleaning methods tested on more realistic simulations

Final aim:

A 21cm **(auto) power spectrum detection** validated with realistic simulations and tested with various and robust cleaning methods

Moving forward

Data:

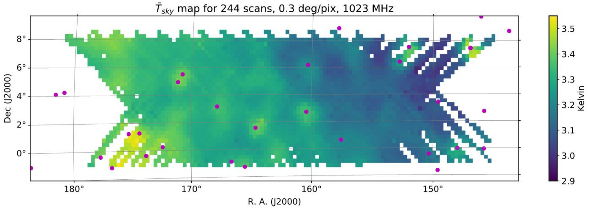
Keep working with pathfinder data (MeerKLASS) to understand the instrument and improve the pipelines

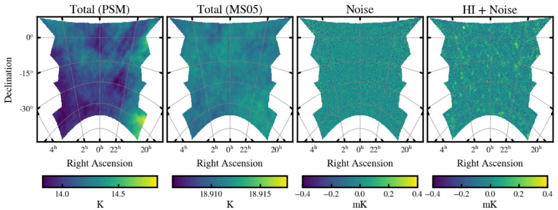
Simulations:

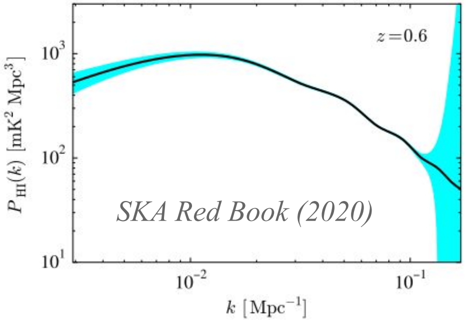
Improve and refine end-to-end simulations

Final aim:

An HI **(auto) power spectrum detection** to extract cosmology and HI properties







- new L band data (41 x 1.5 h)
- UHF band available (higher redshift)

Foreground subtraction challenge
MS et al. 2022

Conclusions

- **The SKA Observatory** will be a powerful machine for **cosmology** with different observables (and their synergies!)
- Main probes: Weak lensing, Continuum, HI galaxies and HI intensity mapping
- **Intensity Mapping** surveys are already taking data with SKA precursors
- **detection in cross-correlation** from MeerKLASS survey x galaxy survey (7.7 σ)
- analysing new data, improving the simulations
- **Prepare for the SKAO era and its potential contribution to the knowledge of large-scale structures**

Please contact me if you are interested in joining the Cosmology SWG!
mspinelli@phys.ethz.ch

Backup

Proposed surveys

Medium Deep Band 2 with SKA-MID

5000 $\deg^2$ and 10.000 h integration time
continuum weak leaning survey and HI galaxy survey out to $z \sim 0.4$

Wide Band 1 with SKA-MID

20000 $\deg^2$ and 10.000 h integration time
continuum galaxy survey and HI Intensity Mapping out to $z \sim 3$

Deep SKA-LOW

100 $\deg^2$ and 5.000 h integration time
following the EoR survey strategy up to the end of Reionization.

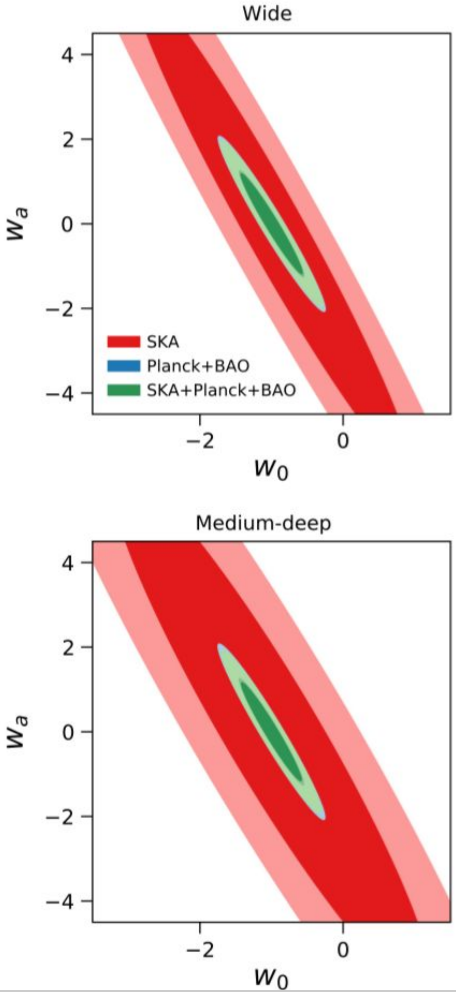
SKA Red Book (2020)

Continuum

SKA will detect million of galaxies of different types (e.g. SFG, FR1 & FR2, radio-quiet quasars)

w0-wa constraint not much better than available ones but possible improvement with better knowledge of bias parameters for each population

Medium Deep survey - Band 2
Wide survey - Band 1



SKA Red Book (2020)

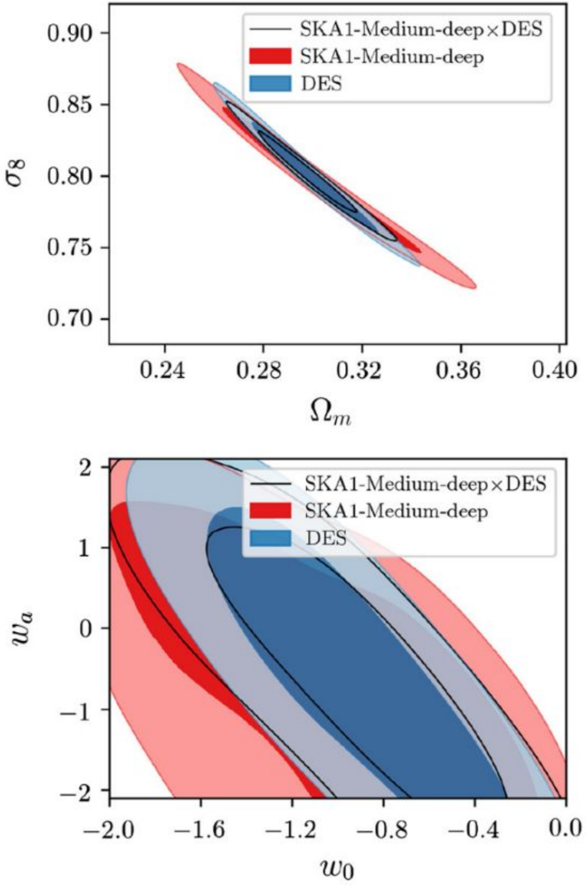
Weak lensing

statistical measurement of the shapes of millions of galaxies

a marginal detection exist
e.g. Chang, Refregier, & Helfand (2004)

SKA comparable constraints with DES
cross-correlation constraints retain almost all of the statistical power of the individual experiments

Medium Deep survey - Band 2



SKA Red Book (2020)

Foreground subtraction challenge

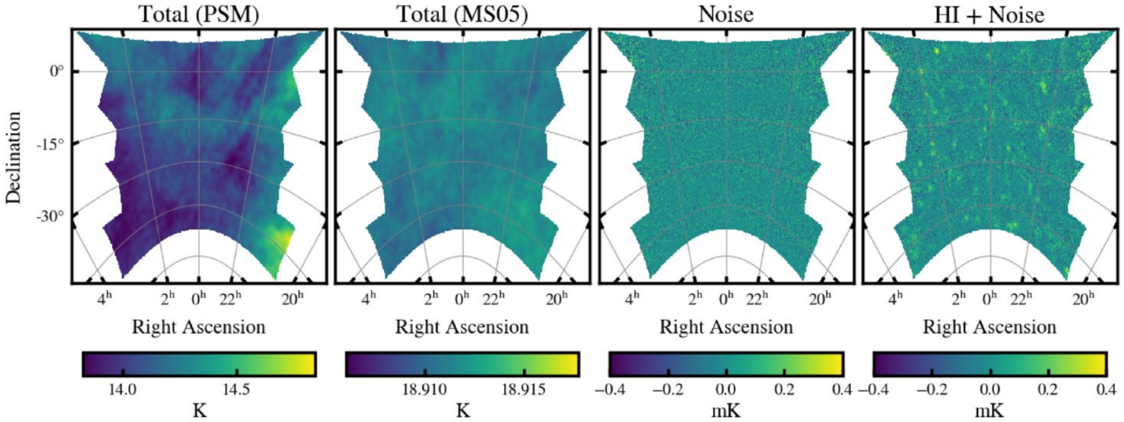
(subset of) **SKA IM Focus Group**

Project setup:

- various foreground models and realistic HI maps
- **instrumental modeling MeerKAT-like and SKAO-like**
- 9 different foreground removal methods (PCA, FastICA, …)

Blind challenge to discover weaknesses and strengths of the various methods

Isabella Carucci, Steve Cunnington, Ze Fonseca, Stuart Harper, Mel Irfan, Alkistis Pourtsidou, Marta Spinelli, Laura Wolz

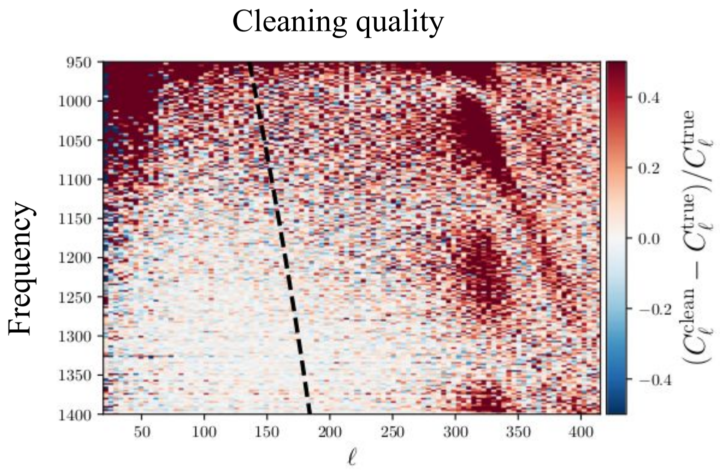


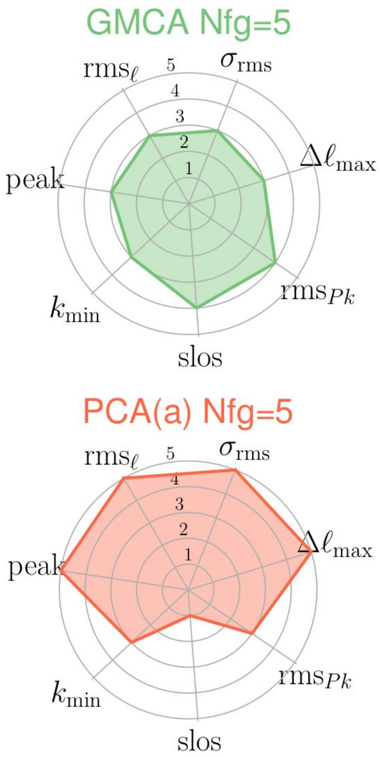
given IM data now, would your favorite method extract the cosmological signal?

Foreground subtraction challenge

- How much can **instrument/foregrounds** coupling impact the signal reconstruction?
- definition of statistics and metrics to evaluate the relative performances

Realistic instrumental effects inevitably complicate the foreground cleaning





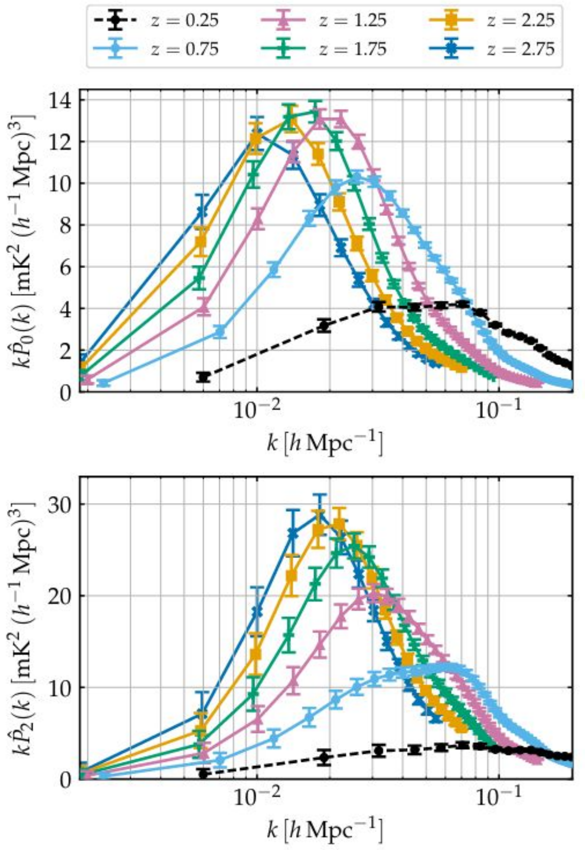
MS et al. 2022

SKAO forecasts

$$P_{21}(z,k,\mu) = \bar{T}_b^2(z)\left[\, b_{HI}(z) + f(z)\,\mu^2 \,\right]^2 P_m(z,k)$$

$$P_\ell(z,k) = \frac{(2\ell+1)}{2}\,\bar{T}_b^2(z)\,P_m(z,k)\int_{-1}^{1} d\mu\,\mathscr{L}_\ell(\mu)\,\left[b_{HI}(z)+f(z)\,\mu^2\right]^2$$

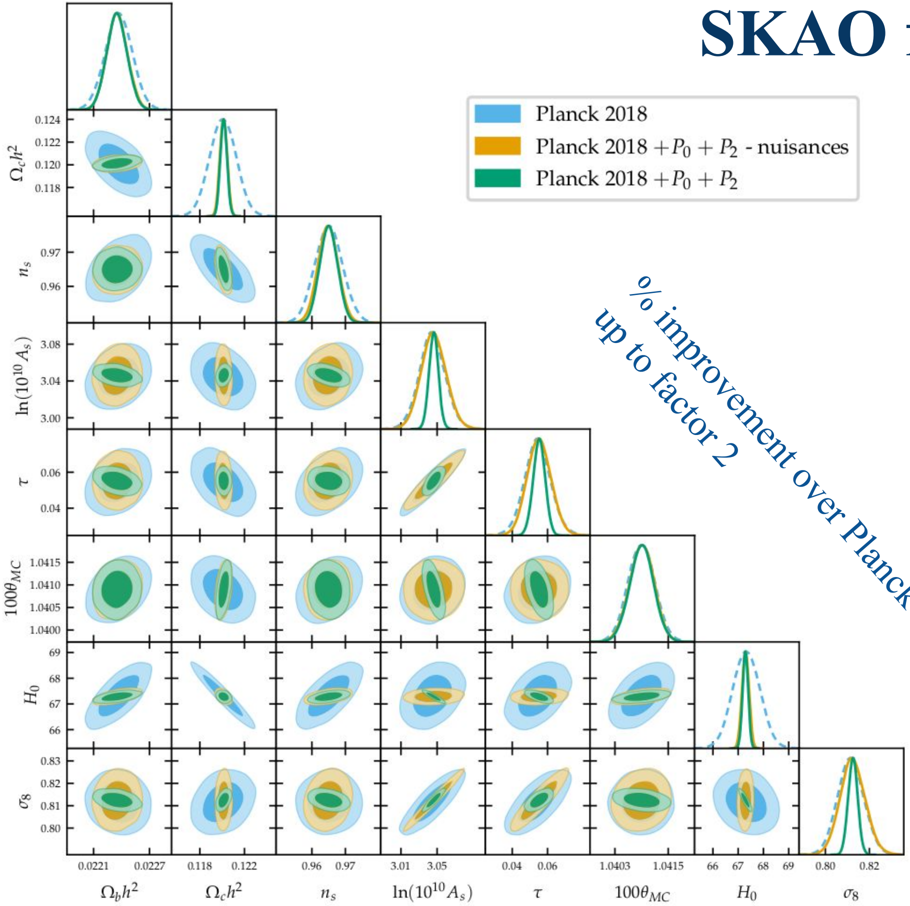
- We consider only monopole and quadrupole l=0,2
- SKA-Mid like observations
  - **tomographic** (6 redshift between 0 and 3)
  - **Single-dish**: beam effect
  - expected noise and sky area



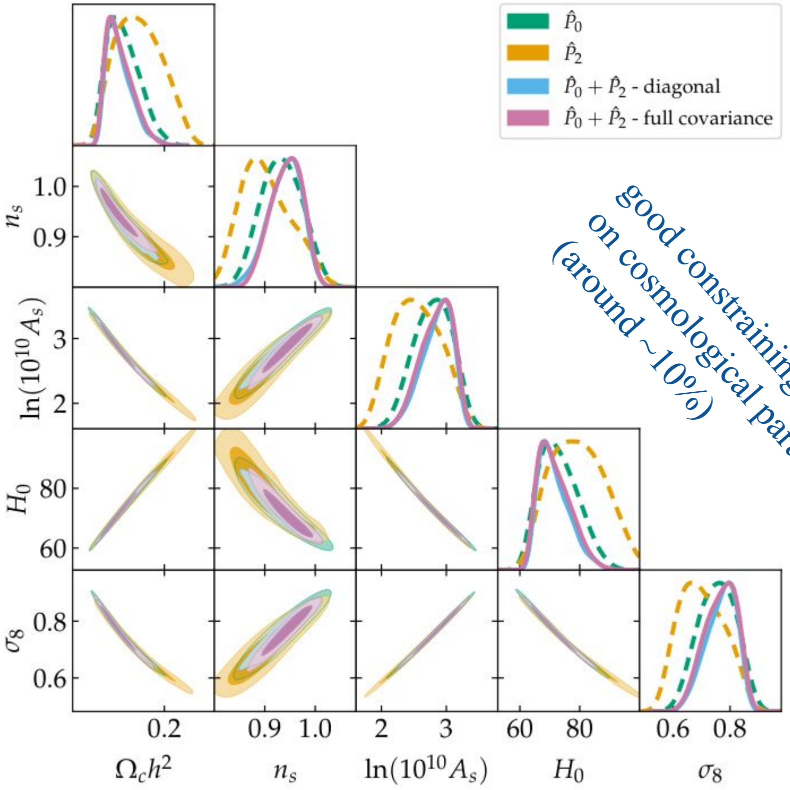
Berti, MS et al. 2022
arXiv:2209.07595

SKAO forecasts

Berti, MS et al. 2022



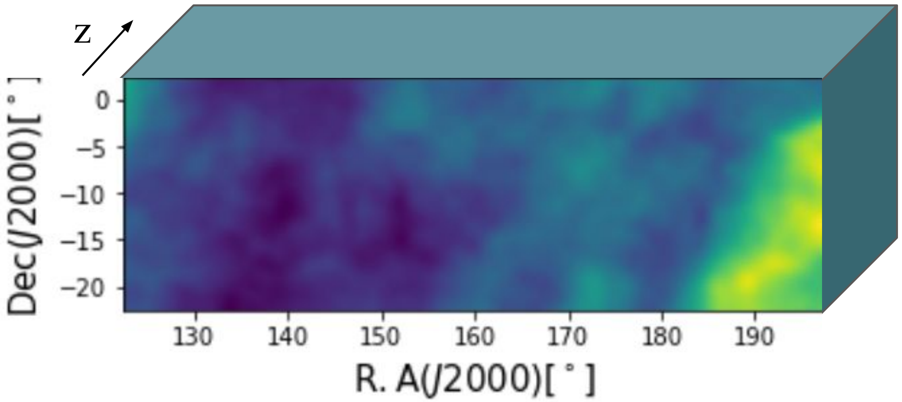
% improvement over Planck
up to factor 2



good constraining power
on cosmological parameters
(around ~10%)

A cleaning example

Mock observation “**cube**”



Simulation includes:

- 100 channels around redshift 0.5
- Foreground contamination:
  Synchrotron, Free-free, point sources
- Gaussian beam
- White noise

$$T = \mathbf{A}s + n + c$$

A mixing matrix of the foreground sources

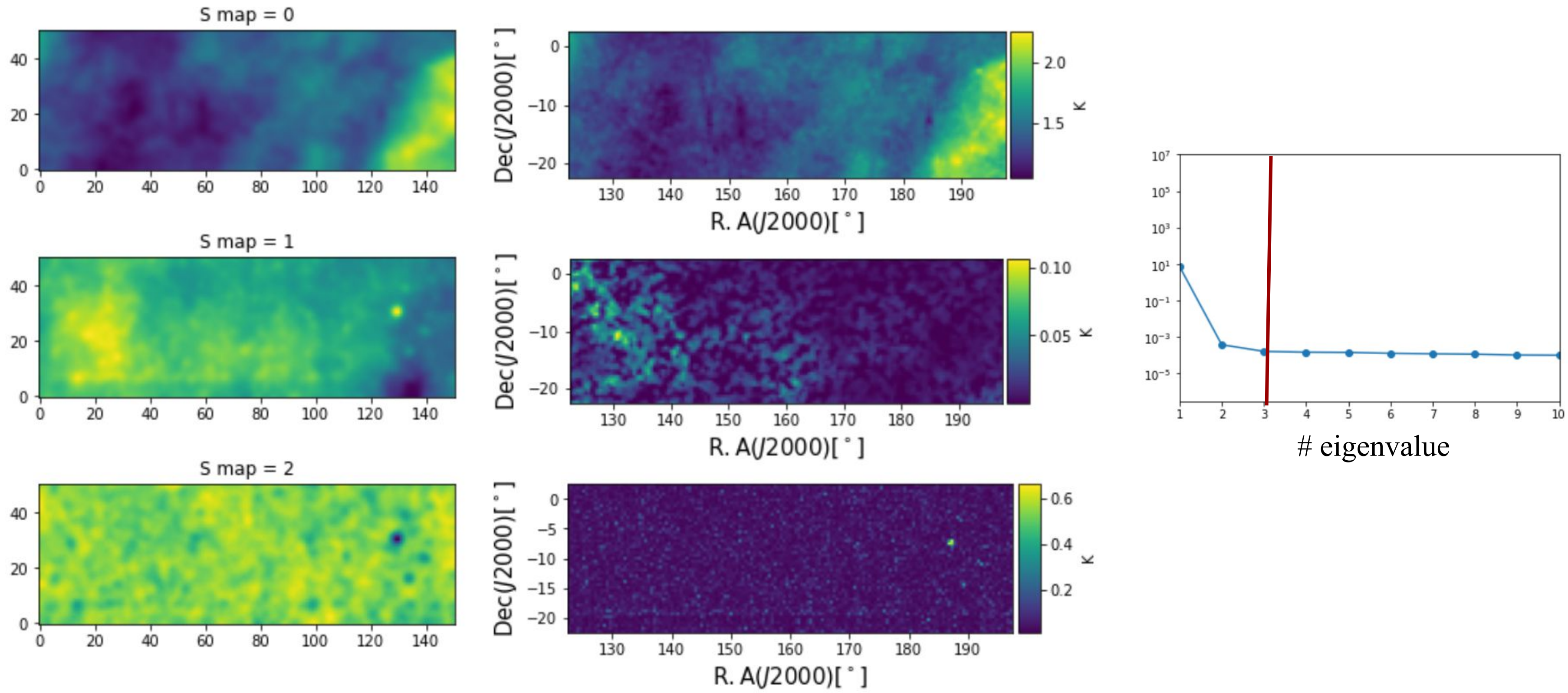
noise

Cosmological signal

How many sources?

$\mathbf{N_{fg}}$ need to be estimated/guessed

A cleaning example



A cleaning example

c+n = T - As

A mixing matrix including only the first Nfg components